

Comparative evaluation of Czech hydromorphological assessment protocols and their transferability to the ecosystem services framework: the Bečva River case study

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ABSTRACT

The assessment of the hydromorphological condition of river corridors represents an established approach for evaluating the quality of fluvial systems. However, the potential to utilize existing hydromorphological assessment protocols and their indicators for the evaluation of ecosystem services remains largely unexplored. This study examines the applicability and robustness of such an indicator – transfer approach using two hydromorphological assessment protocols developed in Czechia (HEM and HYMOS), linked to the CICES 5.1 classification framework. The approach was tested across eight morphologically distinct reaches of the Bečva River, encompassing channelized, renaturalized, and restored segments. Relevant hydromorphological indicators were successfully identified and assigned to eight selected ecosystem services, including regulating, cultural, and provisioning categories. The comparison of HEM and HYMOS, including their respective indicator sets and the resulting ecosystem service assessments, showed that the HYMOS-based transfer generally yielded estimates reflecting a higher ecosystem service capacity. The results also indicate substantially higher ecosystem service capacity in renaturalized and restored reaches, a pattern that is particularly pronounced in the process-oriented HYMOS protocol. At the same time, the study highlights notable uncertainties in the assessment of cultural ecosystem services based solely on hydromorphological indicators. These services are strongly influenced by human perception, suggesting that their robust evaluation requires the integration of sociological data, including stakeholder surveys and participatory research. Overall, the findings demonstrate that hydromorphological assessment protocols can serve as a practical and conceptually consistent basis for the at least a preliminary evaluation of ecosystem service capacity associated with habitat quality, hydrological functioning, and channel-floodplain structure in river corridors.

KEYWORDS

hydromorphological assessment; ecosystem services; Bečva River; river corridors

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1. Introduction

Despite extensive anthropogenic modification resulting from long-term human pressure across most European regions (Scorpio et al. 2024), rivers and their floodplains remain critical landscape components. They provide unique and irreplaceable habitats of high ecological value and function as essential sources of freshwater for human populations, industry, and agriculture (del Tanago 2021; Jakubínský et al. 2021). The growing need to protect and restore landscapes (riverscapes) culminated at the pan-European legislative level in the adoption of the Water Framework Directive, which established an integrated framework for the protection, management, monitoring, and ecological improvement of surface waters across the European Union. To determine the type and degree of modification and regulation of rivers and floodplains, numerous hydromorphological assessment protocols have been developed across European countries, providing structured frameworks for evaluating channel and floodplain alteration (e.g., Raven et al. 1998; Habersack 2000; Rinaldi et al. 2013a). Following the adoption of the Water Framework Directive, hydromorphological assessment became an integral component of ecological status evaluation, supported by the Common Implementation Strategy (CIS) guidance on reference conditions and pressures affecting surface waters (EC 2003a; EC 2003b). As hydromorphological assessment methodologies continued to evolve across Europe, several comparative studies evaluated their strengths, limitations, and conceptual differences, highlighting substantial variation in indicators, spatial scales, and assessment approaches among national methods (Rinaldi et al. 2013b; Belletti et al. 2015). These developments contributed to a gradual shift from habitat-centered assessments towards process-based approaches that better reflect river dynamics and hydromorphological functioning (Rinaldi et al. 2013a). This shift has subsequently been incorporated into recent European standards such as EN 14614:2020 and EN 15843:2025, which emphasize hydrological, sedimentary, and morphological processes, connectivity, and river dynamics across multiple spatial scales (Gurnell et al. 2014). Despite continuous methodological advances, the application of hydromorphological assessment protocols remains associated with several challenges. The interpretation of indicators and the evaluation of river conditions inevitably involve a degree of expert judgement, which may introduce observer-related variability. Consequently, the reliable application of hydromorphological assessment methods requires adequate training and calibration of assessors to ensure consistent and comparable results across different river types.

Over the past two decades, five hydromorphological assessment protocols have been progressively developed also for the evaluation of Czech riverscapes (Demek et al. 2007; Matoušková 2008; Šindlar 2009;

Langhammer 2014; Babej et al. 2024). However, to date, unfortunately none of these methodologies has been systematically implemented within the formal river basin planning process. A major step towards the practical implementation of hydromorphological assessment within river basin management was achieved with the approval of the HYMOS methodology (Babej et al. 2024) by the Ministry of the Environment of the Czech Republic in 2025. The methodology was developed in accordance with the requirements of the Water Framework Directive and reflects recent European developments in hydromorphological assessment, including the principles embedded in the current standards EN 14614 and EN 15843. It provides a basis for hydromorphological assessment and subsequent reporting within the river basin management planning framework coordinated by the Ministry of the Environment.

Ecosystem services (ES) are defined as the benefits that people obtain from ecosystems (Millennium Ecosystem Assessment 2005). Following the IPBES Global Assessment Report (2019), the traditional concept of ecosystem services has been increasingly replaced by the broader and culturally inclusive framework of Nature's Contributions to People (NCP), as formalized in the IPBES glossary and adopted in subsequent assessments. Within the framework of the ICES, these contributions (benefits) are typically grouped into provisioning, regulating and maintenance, and cultural services (Haines-Young, Potschin 2018). A fundamental assumption underlying this concept is that fluvial ecosystems in good ecological and hydromorphological condition, such as structurally and functionally intact rivers and floodplains, possess a higher capacity to deliver a broader range and higher levels of ES, particularly regulating and maintenance services (Jakubínský and Cudlín 2018; Kaiser et al. 2020; Petsch et al. 2023). This relationship is underpinned by the fact that hydromorphological processes and forms constitute a fundamental biophysical basis for the generation of many riverine ecosystem services. Channel-floodplain connectivity, sediment dynamics, hydrological variability, channel planform diversity, and the presence of morphological features such as gravel bars, side channels, or large wood directly influence flood attenuation, nutrient retention, water purification, habitat availability, and biodiversity support (Zhang et al. 2022; Schmidt and Albert 2025). Consequently, hydromorphological indicators may be interpreted not only as descriptors of river condition, but also as proxies reflecting the capacity of river ecosystems to provide selected ecosystem services.

Although the relationship between hydromorphological condition and ecosystem service provision is increasingly recognized (Grizzetti et al. 2016; Müller et al. 2022), practical applications explicitly linking hydromorphological assessment frameworks with ecosystem service evaluation remain relatively scarce. One notable example is the HyMoCARES project,

which explored relationships between river morphology and ecosystem services in Alpine river systems (Carolli et al. 2018). Nevertheless, the potential of existing hydromorphological assessment protocols and their indicators as direct proxies for ecosystem service capacity remains largely unexplored.

Nevertheless, the assessment of ES provided by river corridors remains methodologically challenging, particularly in contexts where systematic biophysical and socio-economic data are often lacking to precisely quantify service quality or magnitude (Hanna et al. 2018; Sousa et al. 2024). Some recent studies have explored the use of remote sensing techniques to spatially and temporally detect the presence and dynamics of selected ES within river corridors (Keele et al. 2019; Poledníková et al. 2025). While such approaches offer valuable large-scale monitoring capacity, the potential of existing hydromorphological assessment protocols to serve as a source of ecosystem service proxies remains largely unexplored. Developing a framework that translates specific hydrogeomorphological parameters into ecosystem service indicators would therefore be highly beneficial. Such an approach could facilitate a more integrated and efficient use of existing monitoring data, allowing hydromorphological assessments to contribute simultaneously to

ecosystem service evaluations and reducing the need for separate data collection efforts.

The aim of this study is to evaluate whether hydromorphological indicators derived from river assessment protocols can be transferred into an ecosystem services framework and used as proxies for selected ecosystem services. To achieve this, we identify and analyze hydromorphological indicators embedded within the two most recent assessment protocols applied to Czech rivers (HEM: Langhammer 2014; and HYMOS: Babej et al. 2024) and assess their relevance for estimating the capacity of river corridors to provide selected ecosystem services. The study seeks to evaluate the applicability and robustness of this indicator-transfer approach under real-world conditions by testing it along a 23-km-long river reach comprising morphologically diverse channel sub-reaches subject to contrasting management regimes.

2. Materials and methods

2.1 Studied reaches and their hydrogeomorphic evaluation

The workflow is designed to apply and critically test two hydromorphological assessment protocols with

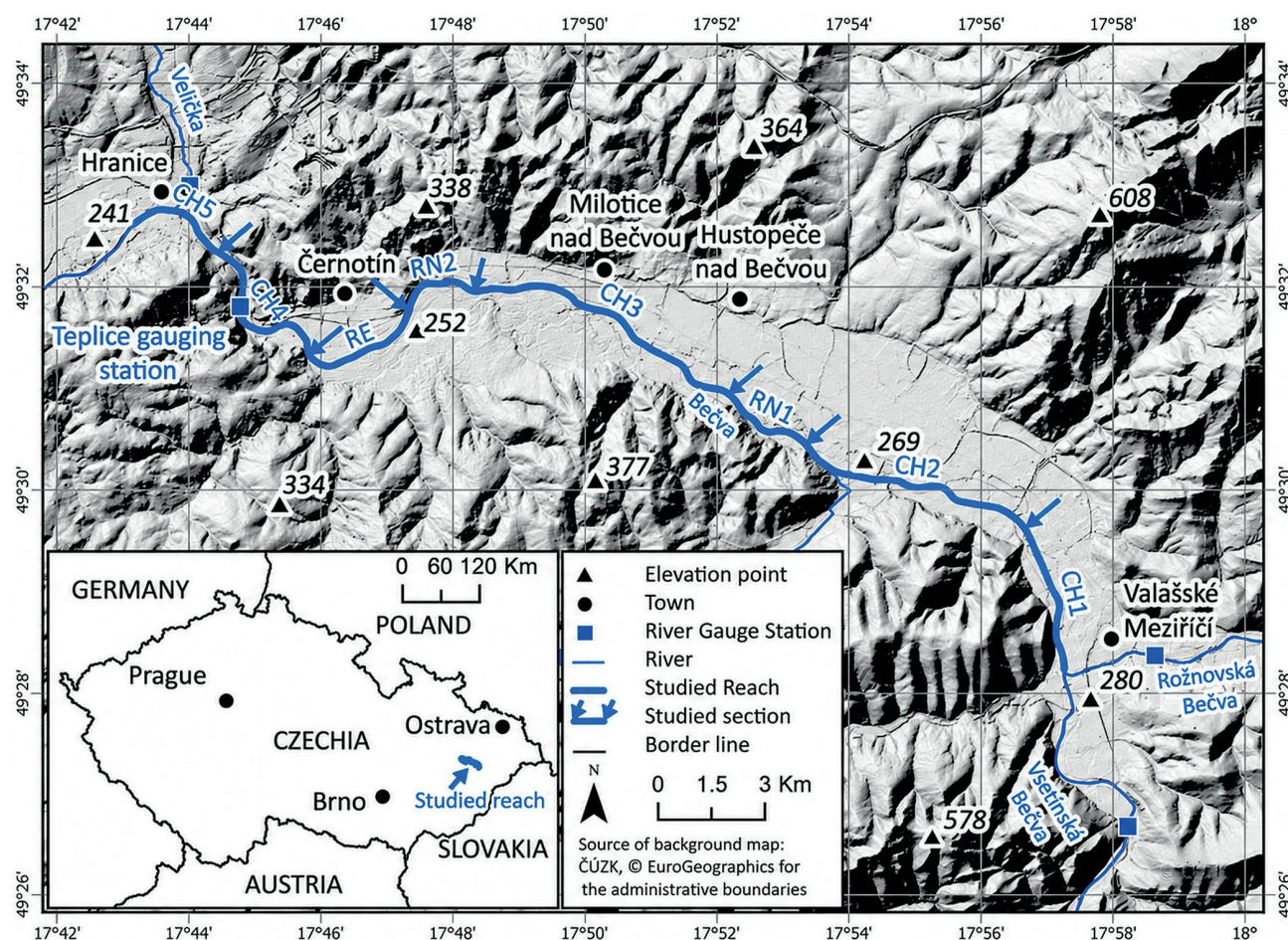


Fig. 1 Geographic position of the study reaches.

Tab. 1 Basic characteristics of evaluated channel reaches.

Reach	River km	Channel characteristics	Floodplain characteristics
CH1	61.5–58.8	Channelized and narrowed reach (riprap embankments), occurrence of boulder ramps	Urban settings (Valašské Meziříčí city), highly modified floodplain
CH2	58.8–54.2	Channelized and narrowed reach, occurrence of boulder ramps	Floodplain forest consisted of natural species, agriculture land
RN1	54.2–52.5	Renaturalized widened reach with a few large wood pieces	Floodplain forest consisted of natural species, agriculture land, a few ponds in the right floodplain
CH3	52.5–47.1	Channelized and narrowed reach (riprap embankments), occurrence of boulder ramps	Floodplain forest consisted of natural species, agriculture land
RN2	47.1–45.6	Renaturalized widened reach, intensive recruitment of large wood from the banks	Floodplain forest consisted of natural species, agriculture land
RE	45.6–43.3	Recently restored widened reach	Agriculture land dominates
CH4	43.3–40.2	Channelized reach (riprap embankments and walls)	Confined narrow urbanized floodplain (Teplice nad Bečvou spa and village), highly modified floodplain
CH5	40.2–38.2	Channelized and narrowed reach (riprap embankments), presence of a weir with strong backwater effect	Urban settings (Hranice city), highly modified floodplain

respect to their capacity to capture not only structural and process-based channel attributes, but also selected ecosystem services. A 23.3-km-long segment of the Bečva River (r. km 61.5–38.2 measured from the confluence with the Morava River) was selected as the

case-study system, including eight spatially contiguous yet morphologically contrasting reaches situated between the cities of Valašské Meziříčí and Hranice (Fig. 1; Tab. 1). The study section includes urbanized segments, channelized reaches in rural settings,



Fig. 2 Representative photographs illustrating the main morphological characteristics of the study reaches: (a) channelized reach CH1; (b) renaturalized reach RN1, developed following flood-induced embankment failures in 1997 and 2010; (c) recently restored reach RE; and (d) channelized reach CH5, strongly influenced by backwater effects associated with a weir.

renaturalized sections, and a recently restored reach (Fig. 2). This longitudinal succession of structurally and functionally distinct channel types provides a robust framework for comparative assessment of hydromorphological condition under contrasting management and disturbance regimes.

The Bečva is a major left-side tributary of the Morava River (total catchment area is 1613 km²), draining a flysch-dominated sector of the Western Carpathians within the extent of the investigated segment. The catchment lithology promotes an intensive, gravel-dominated bedload transport regime that historically supported the development of an anabranching channel pattern prior to systematic channelization during 20th century (Škarpich et al. 2019). Notably, channelized reaches still retain lateral gravel bars, indicating partial preservation of bedload-dominated transport regime. An exception is reach CH4 in Hranice, where channel morphology is strongly influenced by backwater effect induced by a high weir at 38.7 r. km. Two relatively short reaches (RN1, RN2) experienced spontaneous renaturalization following embankment failures during the extreme floods of 1997 and 2010. These disturbances initiated substantial channel widening, increasing bankfull width from the originally channelized 40–50 m to locally up to 180 m. The widening was accompanied by the development of extensive gravel bars, bank failures and localized accumulations of large wood, reflecting renewed lateral mobility and enhanced morphodynamic activity. An additional reach RE was recently restored (2019–2022), transforming a formerly channelized segment into a widened and shallower section with enhanced morphological heterogeneity. Hydrologically, the river exhibits a markedly variable flow regime, characterized by a pronounced disparity between mean annual discharge and the one-year recurrence interval discharge (14.8 and 219 m³/s respectively; ca. 1:15), based on records from the gauging station at Teplice nad Bečvou (r. km 41.4 with contributing catchment area of 1275.5 km²). This high intra-annual flow variability exerts a strong control on channel dynamics and sediment mobility within the study reach.

The two most recent protocols developed to assess the hydromorphological condition of Czech rivers HEM (Langhammer 2014) and HYMOS (Babej et al. 2024) were selected for comparative evaluation. Both frameworks are based on a semi-quantitative scoring system that aggregates multiple parameters describing channel morphology and the adjacent floodplain. The HEM methodology is primarily habitat-oriented, with its monitoring design and assessment framework derived from the original European standard EN 14614:2005. It also relies on relatively strict definitions of reference (near-natural) conditions for individual river types, based on historical sources, particularly maps from the Second Austrian Military Survey dating to the mid-19th century. In contrast, the

HYMOS methodology reflects advances in hydromorphological assessment incorporated in the updated EN 14614:2020 standard, placing greater emphasis on the evaluation of fluvial processes, connectivity, and dynamic channel-floodplain interactions. Rivers are considered as dynamically evolving systems, which allows greater flexibility in defining reference conditions and places greater emphasis on expert judgement. In summary, HEM is particularly suitable for capturing local morphological and habitat diversity, including channel structure and small-scale habitat features. However, its application may be more limited when explicitly assessing process-based aspects of river functioning, such as sediment continuity, hydrological alteration, or migration permeability. By contrast, HYMOS provides a stronger framework for evaluating hydrological and sediment continuity and other process-oriented components of hydromorphological quality. On the other hand, compared with HEM, it provides less detailed information on small-scale habitat structures within the channel. Both protocols classify complex hydromorphological condition using a five-class ordinal scale. For the purpose of direct comparison, the final scores were harmonized and expressed on a unified scale ranging from 1 (high hydromorphological status) to 5 (bad hydromorphological status).

2.2 Linking hydrogeomorphic indicators to ecosystem services

In next step, individual scoring parameters derived from the HEM and HYMOS protocols were integrated into an ecosystem service assessment framework. The Common International Classification of Ecosystem Services (CICES), version 5.1 (Haines-Young, Potschin 2018), was adopted as a standardized and widely applied classification system across diverse landscape types, including river corridors. A transfer scheme was developed to systematically link hydromorphological indicators to eight selected relevant ecosystem services, classified according to the CICES 5.1 framework (codes provided in parentheses): (2.2.1.3) regulation of peak flows; (2.2.5.1) control of erosion rates; (2.1.1.1) water purification; (2.2.2.3) maintenance of nursery habitats (fish); (2.2.1.3) regulation of runoff and baseflow; (4.2.1.2) water supply (surface water as a material resource); (3.1.1.1) recreation (physical use); and (3.1.2.1) aesthetic value. Within the CICES classification, services coded under section “2” represent regulating services, those under “3” correspond to cultural services, and codes beginning with “4” denote provisioning services. The transfer procedure was grounded in expert judgement developed through iterative discussion among the co-authors, whose expertise spans fluvial geomorphology and ecosystem service science. Relevant parameters (indicators) from both hydromorphological assessment protocols were selected

according to their functional relevance to each selected ES. This selection of indicators was not arbitrary but followed a process-based rationale. Indicators were included only when a direct and scientifically justifiable link existed between the assessed hydromorphological characteristic and the ecosystem service considered. A similar expert-based approach was adopted by Keele et al. (2019), who identified linkages between landscape features and land-cover classes mapped from Google Earth imagery and selected provisioning and regulating ecosystem services. In contrast to their study, our approach uses indicators derived from hydromorphological assessment protocols as proxies for ecosystem service capacity. For example, indicators describing floodplain connectivity and hydrological alteration were linked to flood regulation services, whereas indicators representing channel heterogeneity, substrate diversity, and riparian vegetation were linked to habitat-related services. All indicator scores were normalized to ensure comparability among indicators originating from different assessment protocols. Specifically, original scoring ranges (e.g., 0–12 or 1–4) were linearly transformed to a standardized 0–100 scale. Weighting coefficients were assigned based on estimated process relevance of individual hydromorphological indicators to the biophysical capacity of ecosystem services. The final ES score for each reach was calculated as a weighted sum of the normalized indicators. Higher composite scores represent a higher capacity of the river reach to provide the respective ecosystem service. Sensitivity testing indicated that moderate variations in indicator weights ($\pm 10\%$) did not substantially affect the ranking of ecosystem service capacity among the assessed river reaches. Under random modifications of the weighting scheme, the maximum observed change in the final ecosystem service score was 5 points on a 0–100 scale, whereas the average change was only 0.7 point (standard deviation = 1.6).

3. Results

3.1 Comparison of hydromorphological assessment protocols

Tab. 2 presents the hydromorphological assessment results for the eight evaluated reaches. HEM and HYMOS scores are reported as the original numerical outputs of each protocol (i.e., 0–5 for HEM and 0–1 for HYMOS) and harmonized classes.

Both HEM and HYMOS consistently identify higher hydromorphological quality in the renaturalized reaches RN1 and RN2 (Class 2), reflecting enhanced morphological complexity, greater lateral connectivity, and improved process-form coupling relative to the channelized segments. In contrast, reach CH5, influenced by backwater effects from a weir, was classified in the poorest hydromorphological category (Class 5)

Tab. 2 Basic characteristics of evaluated channel reaches.

Reach	HEM score	HEM class	HYMOS score	HYMOS class
CH1	3.81	4	0.34	4
CH2	2.84	3	0.40	3
RN1	1.65	2	0.73	2
CH3	2.75	3	0.49	3
RN2	1.59	2	0.85	2
RE	2.54	3	0.82	2
CH4	3.06	3	0.27	4
CH5	3.51	4	0.18	5

by HYMOS, whereas HEM assigned it a comparatively more favorable rating, similar to the other urbanized reach CH1 (both classified as Class 4). This discrepancy likely indicates a higher sensitivity of the process-oriented HYMOS protocol to longitudinal discontinuity and altered hydraulic conditions. Channelized reaches located in laterally unconfined valley settings, with floodplains characterized by mixed agricultural and forest land use, were consistently assessed as being in moderate condition (Class 3) by both protocols.

3.2 Transfer of hydromorphological indicators to ecosystem services

In the subsequent step, an expert-based evaluation framework was applied to assign individual hydromorphological parameters (indicators), together with weighting coefficients (0.1–0.4), to nine selected ecosystem services (Tab. 3). The weighting scheme reflects the assumed relative contribution of each indicator to the functional provision of a given ecosystem service. Within the HEM protocol, the indicator channel width variability (VNI) was incorporated five times across different ecosystem services, and bank modification (UBR) was assigned four times. In the HYMOS framework, the indicators channel planform pattern (CPP), local hydrological regime alteration (LHR), bank stabilization (BST), and riparian zone and floodplain condition (RFC) were each applied four times. It is important to acknowledge that certain parameters may be conceptually substitutable, either directly or indirectly, within and across the protocols. For example, within HYMOS, floodplain erodibility (FEC) may indirectly correspond to bank stabilization (BST), as both indicators reflect aspects of lateral channel stability. Similarly, lateral channel mobility (BMK) in HEM is functionally comparable to bank modification (UBR), as both parameters capture the degree of artificial confinement and the extent to which natural lateral adjustment processes are constrained.

Fig. 3 illustrates the intensity of individual ecosystem services derived from the indicator transfer scheme (Tab. 3) for both HEM and HYMOS. The results clearly demonstrate that higher ecosystem service provision is consistently associated with the

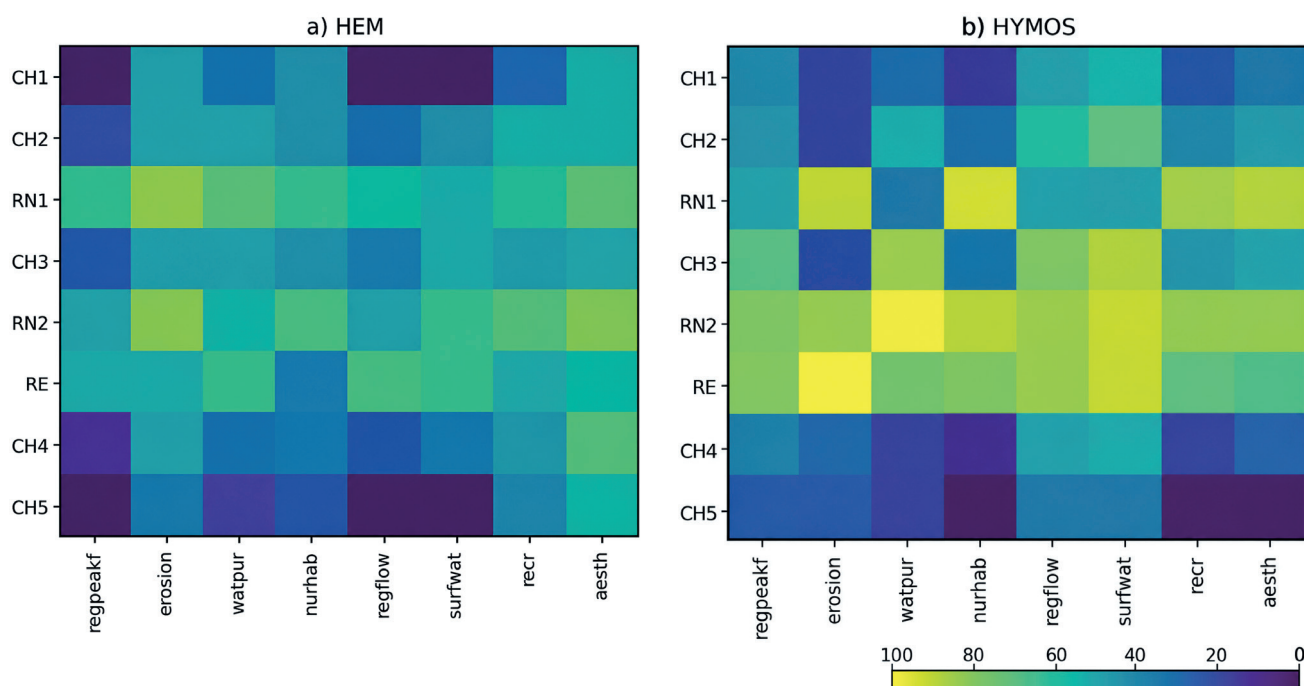


Fig. 3 Heatmaps of ecosystem service scores derived from the (a) HEM and (b) HYMOS protocols for the studied river reaches. Both panels use the same 0–100 scale to allow direct inter-method comparison across service categories and reaches. Higher values indicate higher ecosystem service provision. Abbreviations of ES correspond to Tab. 3.

renaturalized and restored reaches (RN1, RN2, RE), a pattern that is particularly pronounced in the HYMOS-based assessment. Both protocols identify the lowest ecosystem service capacity in the downstream reach CH5, which is strongly affected by the presence of a

high weir and associated impoundment effect that alter flow dynamics, sediment transport, and longitudinal connectivity. Relatively low ecosystem service intensity was also recorded in the upstream channelized reaches located within the urbanized areas of

Tab. 3 Extended mapping of selected CICES 5.1 ecosystem services to hydromorphological indicators including weighting coefficients.

CICES code	Ecosystem service (abbreviation)	Hydromorphological driver	HEM indicators (weight) ^a	HYMOS indicators (weight) ^b
2.2.1.3	Regulation of peak flows (regpeakf)	Floodplain connectivity	VNI (0.30), PIN (0.30), BMK (0.20), OHR (0.20)	FIF (0.30), UHR (0.20), LHR (0.20), BWE (0.15), FEC (0.15)
2.2.1.1	Control of erosion rates (erosion)	Bank stability & channel mobility	BMK (0.35), UBR (0.25), DNS (0.20), STD (0.20)	BST (0.40), LSC (0.30), CPP (0.30)
2.1.1.1	Water purification (watpur)	Water-floodplain interaction	VNI (0.30), PIN (0.25), DNS (0.20), STD (0.15), BVG (0.10)	FIF (0.35), RFC (0.35), LHR (0.30)
2.2.2.3	Maintenance of nursery habitats (nurhab)	Habitat structural complexity	VSK (0.15), VHP (0.15), DNS (0.15), STD (0.15), MDK (0.15), BVG (0.15), UBR (0.10)	CPP (0.20), CSV (0.20), RFC (0.20), BST (0.15), MOR (0.15), LWC (0.10)
2.2.1.3	Regulation runoff and base flows (regflow)	Flow permanence and retention	OHR (0.40), VNI (0.35), PIN (0.25)	UHR (0.30), LHR (0.30), FIF (0.25), BWE (0.15)
4.2.1.1	Surface water used as a material (surfwat)	Hydrological stability	OHR (0.60), VNI (0.40)	UHR (0.20), LHR (0.40), FIF (0.25), BWE (0.15)
3.1.1.1	Recreation – physical use (recr)	Naturalness and accessibility	TRA (0.30), UBR (0.25), VPZ (0.25), VNI (0.20)	CPP (0.35), RFC (0.35), BST (0.30)
3.1.2.1	Aesthetic value (aesth)	Morphological diversity and naturalness	TRA (0.35), UBR (0.30), BVG (0.20), VSK (0.15)	CPP (0.30), RFC (0.30), BST (0.20), SED (0.20)

^aBMK is lateral channel mobility, BVG is riparian vegetation structure, DNS is bed substrate composition, MDK is in-channel large wood, OHR is hydrological regime alteration, PIN is floodplain connectivity, STD is bedform structural diversity, TRA is channel planform modification, UBR is bank modification, VHP is flow depth variability, VNI is floodplain land use, VPZ is riparian zone land use, VSK is channel width variability.

^bBST is bank stabilization, BWE is backwater (impoundment effect), CPP is channel planform pattern, CSV is cross-sectional variability, FEC is floodplain erodibility, FIF is floodplain inundation, LHR is local hydrological regime alteration, LSC is local sediment continuity, LWC is presence of in-channel large wood, MOR is morphological alteration, RFC is riparian zone and floodplain condition, SED is bed sediment pattern, UHR is upstream hydrological regime alteration.

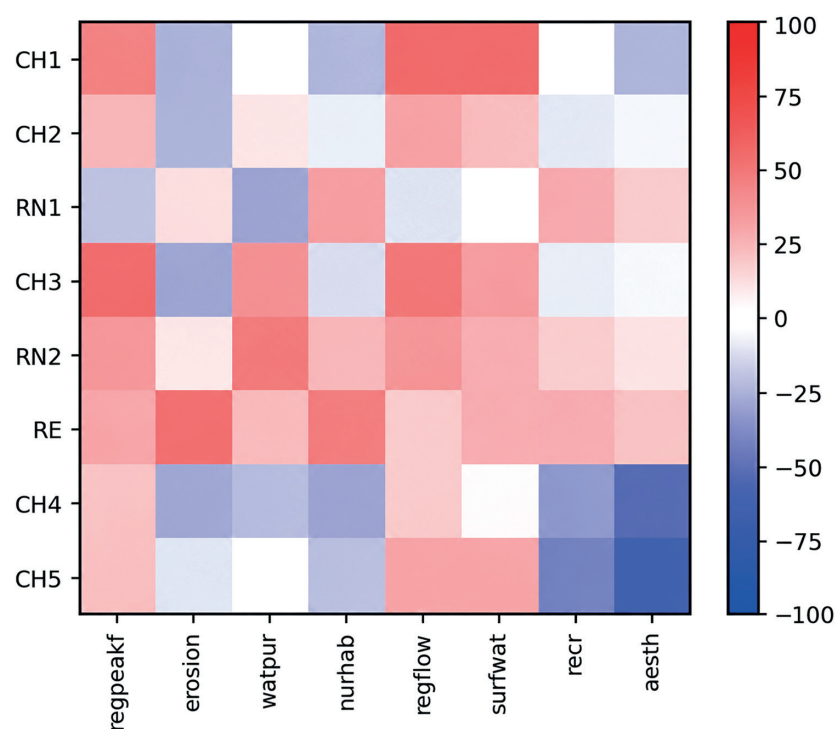


Fig. 4 Difference matrix of ecosystem service scores calculated as the difference between HYMOS- and HEM-derived values (HYMOS – HEM). Positive values indicate higher ecosystem service intensity inferred from HYMOS, whereas negative values reflect higher scores obtained from HEM. Abbreviations of ES correspond to Tab. 3.

Valašské Meziříčí and Teplice nad Bečvou (CH1, CH4), reflecting morphological simplification and reduced floodplain functionality.

A comparison of the two protocols, their respective indicators, and the derived ecosystem service quality indicates a general tendency toward higher ecosystem service values when the HYMOS-based transfer is applied, as illustrated by the difference matrix (Fig. 4). Specifically, in 33 out of 64 cases, HYMOS-derived values exceeded those of HEM by at least 10 points, whereas in 13 cases the difference between the two protocols was less than 10 points. In the remaining 21 cases, HEM produced values higher than HYMOS by at least 10 points. Notably, the renaturalized and restored reaches in the middle section (RN2 and RE) were consistently evaluated more positively by the HYMOS protocol, likely reflecting its higher sensitivity to process-based improvements in channel-floodplain dynamics. In contrast, cultural ecosystem services (i.e., recreation and aesthetic value) were more favorably assessed in the urbanized reaches (CH1, CH4, CH5) when derived from HEM indicators, likely due to their emphasis on structural attributes associated with accessibility and perceived channel stability.

4. Discussion

This study demonstrates that hydromorphological assessment protocols developed for river condition monitoring contain substantial latent information

relevant to ecosystem service provision. The systematic transfer of indicators from HEM and HYMOS protocols into the CICES 5.1 framework revealed consistent spatial patterns of ES capacity along the studied Bečva River, when substantially higher quality of ES was detected for recently renaturalized or restored reaches.

It is noteworthy that, with the exception of Carolli et al. (2018), practical applications explicitly transferring hydromorphological assessment indicators into an ecosystem service framework remain largely absent from the literature. Several studies have suggested the potential of hydromorphological assessments as proxy indicators for ecosystem services (e.g. maintaining populations and habitats) (Maes et al. 2014; Grizzetti et al. 2016). However, these studies did not address the direct use of individual hydromorphological indicators as inputs for ecosystem service assessment. This gap is particularly striking given the conceptual compatibility especially between geomorphic process indicators and regulating ecosystem services. The present study demonstrates that a systematic transfer of hydromorphological indicators to CICES classes is not only conceptually coherent but also methodologically feasible within an operational assessment framework. The normalization of heterogeneous scoring ranges to a 0–100 scale, combined with weighted aggregation, provides a transparent and reproducible computational framework. Partial functional overlap between certain indicators (e.g., FEC vs. BST in HYMOS; BMK vs. UBR in HEM)

reflects structural differences in protocol design but also conceptual convergence in capturing core geomorphic controls such as lateral stability and channel mobility. This redundancy enhances confidence that fundamental process domains are represented across both assessment systems despite methodological divergence. These findings suggest that standardized hydromorphological assessments contain indicators that can serve as proxies for ecosystem service capacity. However, it is important to emphasize that the resulting ES values are strongly dependent on the conceptual transfer scheme applied. In this study, the most frequently utilized indicators were those related to channel width variability and channel planform pattern, as well as bank modification or stabilization, hydrological regime alteration, and the condition of the riparian and floodplain zones across both assessment protocols. Moreover, the weighting structure assigned to individual indicators remains a source of epistemic uncertainty, as the relative contribution of specific geomorphic processes to ecosystem service provision is not empirically uniform and may vary across hydrological and geomorphic contexts.

In particular, renaturalized and restored reaches (RN1, RN2, RE) exhibited markedly higher ES scores, especially for regulating services. These findings support the premise that geomorphic process integrity constitutes a fundamental control on riverine ES capacity. Reaches characterized by widened channels, extensive gravel bar formation, active bank erosion, and large wood recruitment demonstrated enhanced provision of services related to flow regulation, sediment retention, hydrological storage, and habitat maintenance (cf. Verdonchot and Verdonchot 2023). This pattern underscores the central role of process-form coupling in sustaining multifunctional river landscapes. From the management perspective, this also emphasizes arguments for process-based restoration over cosmetic structural modifications (Beechie 2010; Wohl 2024). On the other hand, the strong degradation signal for CH5 detected in both HEM and HYMOS indicates that impoundments severely reduce ES capacity beyond hydropower or bed stabilization trade-offs. Other urbanized reaches (CH1, CH4) exhibit reduced regulating ecosystem services under both HEM- and HYMOS-based transfers, yet comparatively higher cultural services when derived from HEM indicators. This pattern indicates a management tension between aesthetic accessibility and geomorphic functionality. Structurally stabilized channels may enhance perceived order, accessibility, and recreational usability, while concurrently constraining lateral channel dynamics, floodplain connectivity, and sediment transport processes that are fundamental to regulating ecosystem services. The discrepancies in cultural ecosystem service scores between the two methodologies also point to a high degree of uncertainty in defining and operationalizing these service classes. Cultural ES are inherently

perception-dependent and socially constructed, and their evaluation may vary substantially across stakeholder groups. Individuals with natural science backgrounds may favor near-natural, morphodynamically active channel states, whereas residents living in close proximity to rivers may prioritize engineered flood protection measures (e.g., embankments) that enhance perceived safety (Wyzga et al. 2009; Poledníková and Galia 2020).

Several limitations must be acknowledged. First, the assignment of indicators and weights to ES categories is based on expert judgment. The transfer of indicators from hydromorphological assessments to specific ecosystem services benefits from collaboration between both fluvial geomorphologists and ecosystem service specialists, as was the case in this study. Such an interdisciplinary approach helps ensure that hydromorphological processes and ecosystem service concepts are interpreted consistently. Nevertheless, a degree of subjectivity remains unavoidable, particularly in the selection of relevant indicators and the assignment of their relative weights. This is largely because ecosystem services are often difficult to quantify directly and are commonly assessed through proxy indicators and expert judgement rather than direct measurements. Second, the derived ES scores represent potential service capacity rather than quantified service delivery. No independent validation was conducted using ecological, hydraulic, biogeochemical, or socio-economic data (e.g., nutrient retention measurements, fish recruitment metrics or recreational use surveys). The results therefore reflect a biophysical potential framework rather than realized benefits. Finally, the transformation of ordinal hydromorphological scoring into continuous ES capacity metrics assumes quasi-linear relationships between score increments and ecosystem functioning. In reality, certain services may respond nonlinearly to threshold changes in connectivity or inundation frequency.

Future research should prioritize multi-catchment validation across contrasting geomorphic settings (e.g., confined mountain streams or lowland meandering rivers) to rigorously test the transferability and generalizability of hydromorphological protocols as proxies for ecosystem service capacity. Such comparative analyses would clarify the extent to which process-based indicators retain predictive power under differing sediment regimes, valley confinement, hydrological variability, and recent management approaches. In addition, independent validation of ecosystem service proxies is essential. Integration of biotic (e.g., fish and macroinvertebrate assemblages), hydraulic (e.g., inundation frequency), and biogeochemical (e.g., nutrient retention efficiency) measurements would strengthen causal inference between hydromorphological condition and regulating or provisioning services. For cultural ecosystem services, incorporation of sociological research including stakeholder perception surveys and

valuation studies would allow calibration of structural indicators against perceived and realized benefits (Sousa et al. 2024). Finally, the development of automated ecosystem service modules embedded directly within hydromorphological assessment protocols represents a strategic challenge and opportunity. Such integration would enable systematic inclusion of ecosystem service metrics in river basin management plans, particularly within the regulatory frameworks of the Water Framework Directive and the EU Nature Restoration Law. Embedding ES evaluation into existing assessment tools could substantially enhance the policy relevance and operational uptake of ecosystem-based river management.

5. Conclusions

The findings suggest that hydromorphological assessment protocols may be successfully transferred into an ecosystem services framework and used as proxies for the preliminary evaluation of ecosystem service capacity in river corridors, especially for services strongly dependent on habitat quality and the physical functioning of fluvial systems. By systematically transferring indicators into the CICES framework, it is possible to approximate the spatial variability of ecosystem service provision without the need for extensive additional data collection. Despite inherent uncertainties associated with the selection of indicators and the assignment of weighting coefficients, the results exhibit a high degree of internal consistency. Reaches characterized by better hydromorphological condition consistently displayed higher capacity for regulating and provisioning ecosystem services. The study also underscores the limitations of relying solely on hydromorphological indicators for the evaluation of cultural ecosystem services. These services are strongly influenced by human perception, accessibility, and socio-cultural context, which are not fully captured by physical descriptors of channel and floodplain condition. Consequently, the integration of sociological approaches represents a necessary step toward more robust and comprehensive evaluation of cultural ecosystem services. From a practical perspective, the proposed indicator-transfer approach offers a promising pathway for embedding ecosystem service considerations into existing hydromorphological monitoring frameworks and river basin planning processes. This is particularly relevant in the context of European water management policies, where there is increasing emphasis on multifunctionality, nature-based solutions, and sustainable management.

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References

- Babej, J., Jakubínský, J., Němejcová, D., Pechanec, V., Kožený, P., Vyvlečka, P., Výravský, D., Polášek, M., Krásná, K., Straka, M., Cudlín, O., Purkyt, J., Procházková, V., Donoval, J., Štěrbová, L., Včeláková, R. (2024): Metodika hodnocení ekologického stavu útvárů povrchových vod tekoucích (kategorie řeka) pomocí hydromorfologických složek (in Czech); Ústav výzkumu globální změny AV ČR, v. v. i., Výzkumný ústav vodohospodářský T. G. Masaryka, v. v. i., Univerzita Palackého v Olomouci: Brno, Praha, Olomouc; 200 p. Available online: https://funkcnikrajina.com/files/hymos_metodika.pdf (accessed on 15 March 2026).
- Beechie, T. J., Sear, D. A., Olden, J. D., Pess, G. R., Buffington, J. M., Moir, H., Roni, P., Pollock, M. M. (2010): Process-based Principles for Restoring River Ecosystems. *BioScience* 60(3), 209–222, <https://doi.org/10.1525/bio.2010.60.3.7>.
- Belletti, B., Rinaldi, M., Buijse, A. D., Gurnell, A. M., Mosselman, E. (2015): A review of assessment methods for river hydromorphology. *Environmental Earth Sciences* 73, 2079–2100, <https://doi.org/10.1007/s12665-014-3558-1>.
- Carolli, M., Pusch, M., Beichler, S., Costea, G., Zolezzi, G., Geneletti, D., Goltara, A., Boz, B., Habersack, H., Liebault, F., Chouquet, I., Gaucher, R., Javornik, L., Santl, S., Kloetsch, M., Marangoni, N. (2018): Assessing linkages between river morphology and ecosystem services provided by Alpine rivers: the EU HyMoCARES project. *I. S. Rivers* 2018. Available online: <https://www.graie.org/ISRivers/docs/papers/2018/25B52-082CAR.pdf> (accessed on 15 March 2026).
- González del Tánago, M., Martínez-Fernández, V., Aguiar, F. C., Bertoldi, W., Dufour, S., García de Jalón, D., Garófano-Gómez, V., Mandzukovski, D., Rodríguez-González, P. M. (2021): Improving river hydromorphological assessment through better integration of riparian vegetation: Scientific evidence and guidelines. *Journal of Environmental Management* 292: 112730, <https://doi.org/10.1016/j.jenvman.2021.112730>.
- Demek, J., Vatolíková, Z., Mackovčín, P. (2007): Metodika pro hodnocení hydromorfologie na referenčních lokalitách v rámci monitoringu ekologického stavu tekoucích vod podle rámcové směrnice o vodách (in Czech); Agentura ochrany přírody a krajiny ČR: Brno, Czech Republic, 11 p. Available online: https://hymos.czechglobe.cz/mapy/metodika_hymos.pdf (accessed on 15 March 2026).
- European Commission (2003a): Guidance Document No. 10. Rivers and Lakes – Typology, Reference Conditions and Classification Systems; Office for Official Publications of the European Communities: Luxembourg, 87 p. ISBN 92-894-5614-0.
- European Commission (2003b): Guidance Document No. 3. Analysis of Pressures and Impacts; Office for Official Publications of the European Communities: Luxembourg, 148 p. ISBN 92-894-5123-8.
- EN 14614 (2005): Water Quality – Guidance Standard for Assessing the Hydromorphological Features of Rivers;

- European Committee for Standardization: Brussels, Belgium, 21 p.
- EN 14614 (2020): Water Quality – Guidance Standard for Assessing the Hydromorphological Features of Rivers; European Committee for Standardization: Brussels, Belgium, 50 p.
- EN 15843 (2025): Water Quality – Guidance Standard on Determining the Degree of Modification of River Hydromorphology; European Committee for Standardization: Brussels, Belgium, 28 p.
- Grizzetti, B., Lanzanova, D., Lique, C., Reynaud, A., Cardoso, A. C. (2016): Assessing water ecosystem services for water resource management. *Environmental Science & Policy* 61, 194–203, <https://doi.org/10.1016/j.envsci.2016.04.008>.
- Gurnell, A. M., Rinaldi, M., Belletti, B., Bizzi, S., Blamauer, B., Braca, G., Buijse, A. D., Bussettini, M., Camenen, B., Comiti, F., Demarchi, L., Garcia de Jalon, D., Gonzalez del Tanago, M., Grabowski, R. C., Gunn, I. D. M., Habersack, H., Hendriks, D., Henshaw, A. J., Klose, M., Lastoria, B., Latapie, A., Marcinkowski, P., Martinez-Fernandez, V., Mosselman, E., Mountford, J. O., Nardi, L., Okruszko, T., Hare, M. T. O., Palma, M., Percopo, C., Surian, N., van de Bund, W., Weissteiner, C., Ziliani, L. (2014): A hierarchical multi-scale framework and indicators of hydromorphological processes and forms. Research Report; IRSTEA; 237 p.
- Habersack, H. M. (2000): The river-scaling concept (RSC): a basis for ecological assessments. *Hydrobiologia* 422, 49–60, <https://doi.org/10.1023/A:1017068821781>.
- Hanna, D. E. L., Tomscha, S. A., Ouellet Dallaire, C., Bennett, E. M. (2018): A review of riverine ecosystem service quantification: Research gaps and recommendations. *Journal of Applied Ecology* 55(3), 1299–1311, <https://doi.org/10.1111/1365-2664.13045>.
- IPBES (2019): Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Brondizio, E. S., Settele, J., Díaz, S., Ngo H. T. (Eds.); IPBES Secretariat: Bonn, Germany; 1148 p.
- Jakubínský, J., Cudlín, P. (2018): Impact of hydromorphological features of small watercourses on the quality of ecosystem services. In Gastescu, P., Bretcan, P. (Eds.), *Water Resources and Wetlands*, 4th International Conference, Tulcea, Romania, pp. 26–33.
- Jakubínský, J., Prokopová, M., Raška, P., Salvati, L., Bezak, N., Cudlín, O., Cudlín, P., Purkyt, J., Vezza, P., Camporeale, C., Daněk, J., Pástor, M., Lepeška, T. (2021): Managing floodplains using nature-based solutions to support multiple ecosystem functions and services. *WIREs Water* 8(5): e1545, <https://doi.org/10.1002/wat2.1545>.
- Kaiser, N. N., Feld, C. K., Stoll, S. (2020): Does river restoration increase ecosystem services? *Ecosystem Services* 46: 101206, <https://doi.org/10.1016/j.ecoser.2020.101206>.
- Keele, V., Gilvear, D., Large, A., Tree, A., Boon, P. (2019): A new method for assessing river ecosystem services and its application to rivers in Scotland with and without nature conservation designations. *River Research and Applications* 35(8), 1338–1358, <https://doi.org/10.1002/rra.3533>.
- Langhammer, J. (2014): HEM 2014 – Metodika monitoringu hydromorfologických ukazatelů ekologické kvality vodních toků (in Czech); Ministry of the Environment of the Czech Republic: Prague, Czech Republic, 47 p.
- Maes, J., Fabrega, N., Zulian, G., Barbosa, A., Vizcaino, P., Ivits, E., Polce, C., Vandecasteele, I., Rivero, I. M., Guerra, C., Castillo, C. P., Vallecillo, S., Baranzelli, C., Barranco, R., e Silva, F. B., Jacobs-Crisoni, C., Trombetti, M., Lavalle, C. (2014): Mapping and Assessment of Ecosystems and their Services; European Commission, Joint Research Centre, Institute for Environment and Sustainability: Luxembourg, 131 p.
- Matoušková, M. (2008): Ekohydrologický monitoring vodních toků: v kontextu evropské Rámcové směrnice o vodní politice 2000/60/ES (in Czech); Charles University in Prague, Faculty of Science: Prague, Czech Republic, 208 p.
- Millennium Ecosystem Assessment (2005): Ecosystems and Human Well-being: Synthesis; Island Press: Washington, DC, USA, 137 p.
- Müller, H., Hörbinger, S., Franta, F., Mendes, A., Li, J., Cao, P., Baoligao, B., Xu, F., Rauch, H. P. (2022): Hydromorphological Assessment as the Basis for Ecosystem Restoration in the Nanxi River Basin (China). *Land* 11(2): 193, <https://doi.org/10.3390/land11020193>.
- Poledníková, Z., Galia, T. (2021): Photo simulation of a river restoration: Relationships between public perception and ecosystem services. *River Research and Applications* 37(1), 44–53, <https://doi.org/10.1002/rra.3738>.
- Poledníková, Z., Holušová, A., Vaverka, L., Galia, T. (2025): Effects of policy changes in the last 80 years on LU/LC and ecosystem services: A case study of the Odra River floodplain (Czech Republic). *Moravian Geographical Reports* 33(2), 91–105, <https://doi.org/10.2478/mgr-2025-0007>.
- Petsch, D. K., de Cione, V. M., Thomaz, S. M., dos Santos, N. C. L. (2023): Ecosystem services provided by river-floodplain ecosystems. *Hydrobiologia* 850, 2563–2584, <https://doi.org/10.1007/s10750-022-04916-7>.
- Raven, P. J., Holmes, N. T. H., Dawson, F. H., Everard, M. (1998): Quality assessment using River Habitat Survey data. *Aquatic Conservation: Marine and Freshwater Ecosystems* 8(4), 477–499, [https://doi.org/10.1002/\(SICI\)1099-0755\(199807/08\)8:4<477::AID-AQC299>3.0.CO;2-K](https://doi.org/10.1002/(SICI)1099-0755(199807/08)8:4<477::AID-AQC299>3.0.CO;2-K).
- Rinaldi, M., Surian, N., Comiti, F., Bussettini, M. (2013a): A method for the assessment and analysis of the hydromorphological condition of Italian streams: The Morphological Quality Index (MQI). *Geomorphology* 180–181, 96–108, <https://doi.org/10.1016/j.geomorph.2012.09.009>.
- Rinaldi, M., Belletti, B., Van de Bund, W., Bertoldi, W., Gurnell, A., Buijse, T., Mosselman, E. (2013b): Review on Eco-Hydromorphological Methods. REFORM (REstoring Rivers FOR Effective Catchment Management), Deliverable D1.1, European Commission, 7th Framework Programme. Available online: https://www.reformrivers.eu/system/files/1.1_REFORM_DeliverableD1.1_V8_Final.pdf (accessed on 15 March 2026).
- Schmidt, S., Alber, C. (2025): Enhancing multiple ecosystem services: Nature-based measures outperform technical interventions in river management. *Ecosystem Services* 76: 101795, <https://doi.org/10.1016/j.ecoser.2025.101795>.

- Scorpio, V., Comiti, F., Liébault, F., Piegay, H., Rinaldi, M., Surian, N. (2024): Channel changes over the last 200 years: A meta data analysis on European rivers. *Earth Surface Processes and Landforms* 49(9), 2651–2676, <https://doi.org/10.1002/esp.5848>.
- Sousa, M. C., Martins, R., Simões, N. E., Feio, M. J. (2024): Ecosystem services of urban rivers: a systematic review. *Aquatic Sciences* 87: 10, <https://doi.org/10.1007/s00027-024-01138-y>.
- Šindlar, M. (2009): Zjednodušená metodika určená k podpoře činnosti AOPK ČR v oblasti hodnocení zásahů do vodních toků a údolních niv (in Czech); Hradec Králové, Czechia, 20 p.
- Škarpich, V., Galia, T., Ruman, S., Máčka, Z. (2019): Variations in bar material grain-size and hydraulic conditions of managed and re-naturalized reaches of the gravel-bed Bečva River (Czech Republic). *Science of The Total Environment* 649, 672–685, <https://doi.org/10.1016/j.scitotenv.2018.08.329>.
- Verdonschot, P. F. M., Verdonschot, R. C. M. (2024): Ecological Functions and Management of Large Wood in Fluvial Systems. *Current Forestry Reports* 10, 39–55, <https://doi.org/10.1007/s40725-023-00209-x>.
- Wohl, E., Rathburn, S., Dunn, S., Iskin, E., Katz, A., Marshall, A., Means-Brous, M., Scamardo, J., Triantafyllou, S., Uno, H. (2024): Geomorphic context in process-based river restoration. *River Research Applications* 40(3), 322–340, <https://doi.org/10.1002/rra.4236>.
- Wyzga, B., Zawiejska, J., Le Lay, Y.-F. (2009): Influence of academic education on the perception of wood in watercourses. *Journal of Environmental Management* 90(1), 587–603, <https://doi.org/10.1016/j.jenvman.2007.12.013>.
- Zhang, C., Kuai, S., Tang, C., Zhang, S. (2022): Evaluation of hydrological connectivity in a river floodplain system and its influence on the vegetation coverage. *Ecological Indicators* 144: 109445, <https://doi.org/10.1016/j.ecolind.2022.109445>.